

PHYSICAL AND CHEMICAL ASPECTS OF FIRE SUPPRESSION IN EXTRATERRESTRIAL ENVIRONMENTS

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INTRODUCTION

A fire, whether in a spacecraft or in occupied spaces on extraterrestrial bases, can lead to mission termination or loss of life. While the fire-safety record of US space missions has been excellent, the advent of longer duration missions to Mars, the moon, or aboard the International Space Station (ISS) increases the likelihood of fire events, with more limited mission termination options. The fire safety program of NASA's manned space flight program is based largely upon the principles of controlling the flammability of on-board materials and greatly eliminating sources of ignition. As a result, very little research has been conducted on fire suppression in the microgravity or reduced-gravity environment. The objectives of this study are: to obtain fundamental knowledge of physical and chemical processes of fire suppression, using gravity and oxygen concentration as independent variables to simulate various extraterrestrial environments, including spacecraft and surface bases in Mars and moon missions; to provide rigorous testing of analytical models, which include comprehensive descriptions of combustion and suppression chemistry; and to provide basic research results useful for technological advances in fire safety, including the development of new fire-extinguishing agents and approaches, in the microgravity environment associated with ISS and in the partial-gravity Martian and lunar environments.

MOTIVATION

As the planned extraterrestrial missions aim to establish long-term, human-occupied bases on Mars and the moon, fire incidents are possible. Friedman [1] reviewed the understanding and key issues of fire safety in the low-gravity extraterrestrial environments. Fire safety technology must be tailored to respond to the unusual fire characteristics in low-gravity environments. Unusual environmental conditions and agent usage peculiar to extraterrestrial applications may exert distinct influences on the flame structure, and, in turn, on the various physical and chemical processes in fire suppression and agent effectiveness.

Materials fire-spread tests on the ground at normal earth gravity (1 g) are justified by the view that the buoyancy-aided combustion represents a "worst case". However, because the flame structure significantly differs with the gravity level, various fire phenomena may not be simply interpolated from results in normal and microgravity. For example, the flammability and flame spread data for thin-paper fuels [2] showed that the maximum flame-spread rate occurred in partial-gravity (Martian) environments (0.38 g).

In quiescent microgravity environments, the solid fuel combustion intensities are reduced, yet a fire suppression agent and/or its decomposed inhibition species may also diffuse more slowly into the flame zone. Nonetheless, spacecraft and surface base atmospheres include forced convection (typically a continuous flow in the range of 6 to 20 cm/s) for atmospheric conditioning and component cooling [3]. For thin cellulosic fuels, low-velocity forced flow

greatly increases the flame spread rate and flammability range in microgravity [2]. In addition, application of a fire-extinguishing agent toward an established fire may cause a substantial current of agent-air mixture and alter the fire dynamics, changing the agent dispersion and interaction with the flame zone. Finally, for uncontrollable fires, a last-resort procedure is to evacuate the crew to a safe haven and then depressurize the module in an attempt to extinguish the fire [1, 4]. The depressurization may induce a significant airflow, which could augment burning, and stabilization of the fire in a recirculation zone behind an obstruction could also occur. In a 1-g experiment, a step-stabilized flame was very stable and attached to the obstruction at the free air velocity up to ~ 3 m/s [5, 6]. The unsteady vortex-flame interaction leading to local extinction has been studied numerically in 1 g [7], but unsteady suppression phenomena are unstudied for low-gravity environments.

Oxygen-enriched atmosphere, likely to be used in spacecraft and surface bases in the Mars missions, may result in intense burning and cause serious difficulties in suppression of established fires. The Space Shuttle and ISS environments that are prescribed for crew conditioning prior to extravehicular activities are 30-vol% oxygen in nitrogen at 70.3 kPa [3]. Such high oxygen concentration causes attendant increased fire hazards. The Mir fire in February 1997, caused by the failure of a solid-oxygen generator, is a good example of the difficulty in predicting potential fire scenarios in spacecraft [3] and suppressing the oxygen-assisted fires. Although microgravity flame-spread experiments in oxygen-enriched atmospheres have been conducted [2], the agent performance data is limited to the earth atmosphere [8].

A fire suppressant itself such as CO₂ may possibly be used in crew-compartment atmospheres. The effectiveness of various agent types needs to be studied in realistic extraterrestrial environments. The Space Shuttle uses fire extinguishers with halon 1301 (CF₃Br); the production of which has been banned due to its high stratospheric ozone depletion potential [9]. ISS uses CO₂ or H₂O as the agent, but these agents are relatively inefficient. Although the existing systems may continue to be used, new agents or techniques are ultimately needed to replace the Shuttle halon system; for long-duration missions aboard ISS, alternatives to the CO₂ systems are desirable [4]. Innovations can be developed for habitation and extinguishment of in-situ resource utilization using the Martian atmosphere (95.3-vol% CO₂) as the agent [4]. Although chemical agents can yield toxic and corrosive byproducts, and are unlikely to be used for long-duration missions, they are an order-of-magnitude more efficient and may be appropriate under some conditions.

RESEARCH APPROACH

In this study, both experimental and computational approaches are pursued. The experiments include both normal- and reduced-gravity tests using the drop tower and aircraft. For normal gravity conditions, the cup burner apparatus is the most widely used test for suppressant effectiveness by the fire protection community. An agent is generally introduced into the co-flowing oxidizer in the cup-burner system to determine the critical agent mole fraction at extinction. Because its structure resembles a fire, great faith has been placed in suppressant extinction concentrations determined in the cup burner experiment, and many codes and design standards are based on the cup-burner values [8]. Using a cup burner, the critical extinction mole fraction of fire suppression agents will be measured for selected fuels with variable gravity and

oxygen concentration in the oxidizer. Such cup-burner tests will connect the results in reduced gravity to the vast existing database on flame extinction obtained in 1 g. Then, physical and chemical effects of agents on flame structure and suppression processes will be determined with variable gravity and oxygen concentration in the oxidizer. Physical aspects include agent injection, dispersion, and entrainment as well as the thermal effects of the agent on flame structure. Chemical aspects include impacts on agent effectiveness, mechanistic processes of suppression (radical recombination and entrapping), and the effect of flame structure on a shift in important reactions.

Figure 1 shows conceptual schematics of the burner configurations. The axisymmetric cup burner is the standard burner used for the critical agent mole fraction measurements for various agents and fuels in normal gravity. The standard burner has the cup and chimney diameters of 30 mm and 80 mm, respectively. The 2D burners have a longer optical path along the flat flame sheet and uniform properties along the path, which are advantageous for optical measurements. In addition, an agent can be injected toward the flat flame formed on the step burner for the agent flow-flame interaction studies. Diagnostic techniques to be used include Mach-Zehnder interferometry, particle image velocimetry, standard color videography and high-speed digital color imaging.

Major parameters to be varied are the gravity level, oxygen mole fraction in the oxidizer, oxidizer velocity, and types of agent, fuel, and diluent. Fuels include gases: CH_4 , CH_4/N_2 , $\text{CH}_4/\text{N}_2/\text{O}_2$, liquids: $n\text{-C}_7\text{H}_{16}$, and solids: $3[\text{CH}_2\text{O}]$; and diluents include N_2 , CO_2 , He, and Ar. In addition to N_2 , CO_2 , H_2O , we will also study agents which have an increasing chemical contribution; namely CF_4 , CF_3H , CF_3Br , and $\text{Fe}(\text{CO})_5$ (or ferrocene). These halogenated compounds provide a homologous series with very similar physical contributions but increasing chemical effect. The iron compound is included, not to so much as a potential agent, but rather to determine the limit of what is possible through chemical inhibition. Recent research has shown that $\text{Fe}(\text{CO})_5$ up to 100 ppm behaves as a nearly ideal catalytic agent, with the radical recombination reactions proceeding at nearly gas-kinetic rates [10, 11]. Hence, it can be added as a diagnostic tool to determine the effect from gas-phase radical recombination alone.

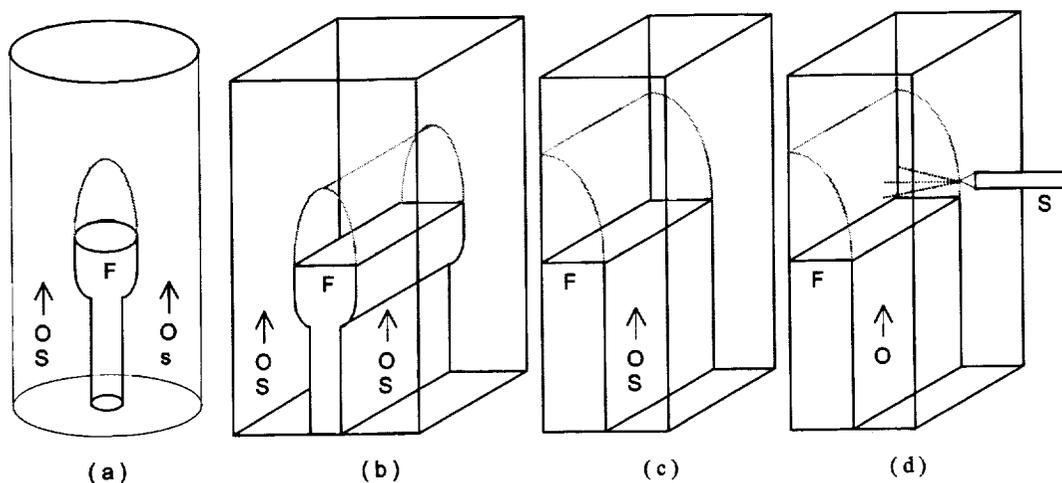


Fig. 1 Burner configurations. (a) Axisymmetric cup burner, (b) 2D cup burner, (c) step burner, (d) step burner with agent injection. F: fuel, O: oxidizer, and S: suppressant.

Computations of laminar, unsteady diffusion flames play an important role in understanding combustion and suppression phenomena. In this study, unsteady fire suppression processes in various flames will be simulated under different gravity and oxygen levels using an existing transient two-dimensional code (known as UNICORN [12]), which includes comprehensive kinetic models for the CH₄-O₂ combustion including diluents (GRI Mech) and halogenated agent chemistry (NIST CKMech). A periodically oscillating, pure-methane-air jet diffusion flame has been recently [13] studied to explore the chemical inhibition resulting from CHF₃. Furthermore, additional goals of the project include extension of the code to higher hydrocarbon fuels such as C₃H₈ and n-C₇H₁₆, incorporation of a radiation model and the detailed kinetics models for various fire suppressants, and evaluation of various models developed in this study by a comparison with benchmark experiments.

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